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THORIUM/NEODYMIUM COSMOCHRONOLOGY AND GALACTIC CHEMICAL EVOLUTION

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Abstract

We emphasize the importance of galactic chemical evolution and the different nucleosynthetic origins for thorium and neodymium with regards to the recent observations of neighboring spectral lines from these elements in G-Dwarfs stars and the use of the correlation of the spectral line ratio with stellar age to derive an upper limit to the age of the galaxy. When effects of galactic chemical evolution and nucleosynthetic origin are included the systematic trend in the data toward constant or even increasing Th/Nd ratio with stellar age can be easily understood. A model dependent (3σ) best upper limit of $T_0 \approx 13$ Gyr to the age of the galaxy is derived, although simpler schematic models for the evolution of the Th/Nd ratio can give (3σ) upper limits ranging from 9 to 20 Gyr.

Subject Headings: stars: abundances - galaxies: evolution - galaxies: The Galaxy - nucleosynthesis

I. Introduction

Recent observations (Butcher 1987) of close lying thorium and neodymium lines for a number of G-dwarf stars have led to the suggestion that the line strength ratio of Th (most likely due to unstable ^{232}Th ($\tau_{1/2}$ = 14 Gyr) to stable Nd could be used as an indicator of the age of the galaxy. Based upon the observation that the Th/Nd line ratio shows little variation as a function of stellar age, an upper limit to the age of the galaxy of 9.6 Gyr was derived which is somewhat lower than (although marginally consistent with) the age derived from other chronometers (Cowan, Thielemann, and Truran 1986; Fowler and Miesl 1986; Meyer and Schramm 1986; Fowler 1987; Winget, et al. 1987) for which $T_0 \sim$ 15±5 Gyr. It should be noted that there is a lower bound from nucleochronology mean age studies of 8.7 Gyr (Meyer and Schramm 1986) based upon assuming all production at t = 0. Thus, to have galactic ages close to this number would require the other chronometers to be produced very early. This seems unlikely since ^{244}Pu ($\tau_{1/2}$ = 8.2x10^7 yr) was present when the solar system formed, and is inconsistent with the model of constant Th and Nd production assumed in Butcher (1987).

The use of the Th/Nd stellar line ratio could be a significant means of determining galactic age because it would be the only nuclear cosmochronometer derived from material outside the solar system. Also since observations are made on stars of different galactic ages it may be possible to better understand the galactic chemical evolution parameters for this chronometer. In this letter, however, we wish to highlight two difficulties associated with utilizing this chronometric ratio which can significantly affect the derived upper limit to the galactic age and possibly eliminate the above mentioned inconsistencies.

The first and most important difficulty is due to the different stellar mechanisms (Mathews and Ward 1985) contributing to the abundances of these elements. Although ^{232}Th is surely only produced in an explosive rapid-neutron-capture environment (the r-process), neodymium isotopes are contributed to by both the r-process and quiescent slow neutron capture (the s-process). This difference was alluded to in Butcher (1987) but not used in the analysis, even though it was pointed out that one star in the sample is over abundant in s-process elements by a large factor. The relative s-process and r-process contributions to neodymium have recently been analyzed in detail (Mathews and Kappeler 1984, Howard, et al., 1986). From these analyses one can conclude that almost 50% of the solar-system neodymium abundance is of a stellar origin completely distinct from that responsible for thorium. These different stellar origins should be associated with the different galactic evolution histories of s- and r-process elements (Schramm and Tinsley 1974). Indeed, there are by now numerous observations (Spite and Spite 1978; Sneden and Parthasarathy 1983; Luck and Bond 1985; Sneden and Pilachowski 1985) indicating enhanced r-process to s-process abundances in metal poor stars. The implication of these data are that the Th/Nd production ratio could have been significantly higher in the past.

A second important feature to consider is the additional destruction term due to the loss of Nd and Th from the interstellar medium (ISM) by star formation and subsequent trapping of material into stellar remnants. In Butcher (1987) the differential equation governing the abundance, N_i, of species, i, was assumed to have the form;

$$dN_i/dt = P_i p(t) - \lambda_i N_i \ , \tag{1}$$

where P_i denotes the relative production of species, i, according to a time-dependent process p(t), and λ_i is the nuclear decay rate, ($\lambda_{Th} = 0.049$ Gyr^{-1}, $\lambda_{Nd} = 0$). Equation (1), is missing an additional linear term (Schramm and Wasserburg 1970; Schramm 1974), $-BN_i$ where B is the net loss of material from the interstellar medium due to star formation, remnant trapping, etc. As we shall see, neglecting this term could minimize the effects of ^{232}Th decay, and thus lead to a larger age for the galaxy.

In what follows we utilize a model which includes both the additional destruction due to star formation, and the different production histories for ^{232}Th and Nd. In the context of this model we find that it is imperative to include both of these effects. Doing so improves the fit to the data and allows for substantially different galactic ages.

II. Galactic Chemical Evolution

Including the additional terms into the differential equation for the rate of change of species, i, we write;

$$dN_i/dt = P^s{}_i p(t)^s + P^r{}_i p(t)^r + E_i(t) - B(t)N_i - \lambda_i N_i \ , \tag{2}$$

where $P^j{}_i p(t)^j$ are source terms for r- and s-process material, $E_i(t)$ is the contribution from the ejection from stars which have not destroyed or added to their initial Th or Nd abundance, and B is the fractional rate of loss of mass from the interstellar medium due to star formation. In Eq. (2) we have explicitly assumed that there is no contribution from infalling extragalactic s-process or r-process material. We also implicitly neglect radial mixing in the disk.

All of the quantities in Eq. (2) can be defined in terms of standard separable galactic chemical evolution models (Audouze and Tinsley 1976), based upon an initial mass function, $\phi(m)$, and a stellar birthrate function, $f(t)$. The fractional birthrate, B, is;

$$B = \int dm\ m\ \phi(m) f(t)/M_G(t) \quad , \tag{3}$$

where M_G is the mass of the interstellar medium. Similarly, the source terms in Eq. (2) become;

$$P^j{}_i p(t)^j = \int dm\ (m-m_r)\ \phi(m) f(t-\tau(m)) X^j{}_i(m) \quad , \tag{4}$$

where m_r is the mass of the stellar remnant for a star of initial mass, m, which dies after an age $\tau(m)$, and $X^j{}_i$ is the mass fraction of species, i, in the ejecta. For the ejection, $E_i(t)$, from non r- or s-process stars, the expression is the same as Eq. (4) but with the $X^j{}_i$ given by the star's initial mass fraction for Th or Nd. Therefore, in what follows we absorb $E_i(t)$ into the source terms, $P^j{}_i p(t)^j$. The total rate of change of the mass of the interstellar medium is just given by,

$$dM_G/dt = -BM_G + P(t) + R(t) \quad , \tag{5}$$

where P is the total rate of mass ejection from stars,

$$P(t) = \int dm\ (m-m_r)\ \phi(m)\ f(t-\tau(m)) \quad , \tag{6}$$

and R is the rate of extragalactic infall.

III. r-process and s-process production functions

Although the details of the mechanism for s-process nucleosynthesis are still being debated, (Iben and Truran 1978; Cosner Iben and Truran 1980; Mathews, et al. 1986; Howard, et al. 1986; Malaney and Boothroyd 1987) it is now widely accepted that the s-process occurs during the thermal pulse phase of asymptotic giant branch stars (Iben 1977). This restricts the range of stellar masses to those in which shell helium burning occurs above an electron-degenerate carbon-oxygen core. This places an upper limit (Iben and Renzini 1983) on the initial mass of such stars of about 8-9 $M_\odot$ depending on the composition. For the lower initial mass limit, stars as small as 0.8-1.0 $M_\odot$ eventually enter the thermally pulsing AGB phase. The enrichment of s-process material in the outer envelope, however, requires core masses greater than 0.6 $M_\odot$. Allowing for mass loss from the main sequence, this places a lower limit of about $1M_\odot$. For the purposes of this study we therefore consider s-process elements to occur in the mass range of 1.0-9.0 $M_\odot$. The mass fraction of produced Nd will be primarily a function of the neutron exposure and the initial Fe abundance (Mathews and Ward 1985). For the purposes of this study, however, we will assume, for simplicity, a constant s-process mass fraction as a function of stellar mass. This is not an altogether unreasonable assumption since neutron exposures similar to that experienced by the solar-system material are observed on S stars and Ba stars (Mathews, et al. 1986) and Fe may not vary too rapidly in time (Tinsley 1977) after an initial prompt enrichment. In a future study we will consider the effect of the time dependence of the metallicity and the variation of neutron exposure with stellar mass in more detail. These effects could increase the inferred galactic ages by delaying the appearance of s-process neodymium, and thus increasing the Th/Nd ratio for old stars.

The site for the r-process is much less well understood (Norman and Schramm 1979; Mathews and Ward 1985) than for the s-process. Numerous sites have been proposed such as ejection of neutronized core material from a supernova, shock-induced explosive helium burning, or neutron-star collisions. Most proposed sites are associated in one way or another with massive star evolution, $M \geq 9\ M_{\odot}$, and the most viable sites at the present time involve the build up of r-process material from a neutronized gas, independent of the presence of preexisting "seed" material. Indeed, observationally it appears that the r-process elements are primary (Truran 1981). Thus, we assume a constant r-process mass fraction for massive stars independent of initial composition.

IV. Model Calculations

The general solution to equation (2) for the observed abundance at time T_0 on a star which formed at time, T, after the birth of the galaxy is;

$$N_i(T_0) = \exp(\lambda_i(T-T_0))\exp(-\int_0^T(\lambda_i+B)dt)$$

$$\times [\int_0^T P^s{}_i p(t)^s \exp(\int_0^t(\lambda_i+B)d\tau)dt$$

$$+ \int_0^T P^r{}_i p(t)^r \exp(\int_0^t(\lambda_i+B)d\tau)dt] \quad (7)$$

for which the Th/Nd ratio is

$$Th/Nd = \exp(-\lambda T_0)\int_0^T P^r{}_{Th} p(t)^r \exp(\int_0^t(\lambda+B)d\tau)dt$$

$$\times [\int_0^T P^r{}_{Nd} p(t)^r \exp(\int_0^t Bd\tau)dt$$

$$+ \int_0^T P^s{}_{Nd} p(t)^s \exp(\int_0^t Bd\tau)dt]^{-1} . \quad (8)$$

We consider this solution in three simple models.

model a) no loss term; constant equal production functions

Consider first the limit used in Butcher (1987) in which $B = 0$, and $X^s{}_{Nd} = 0$. Then for a constant r-process production rate, the ratio of Th/Nd for a star formed at time, T, becomes;

$$Th/Nd = (P_{Th}/P_{Nd})\exp(-\lambda T_0)[\exp(\lambda T)-1]/(\lambda T) \ , \qquad (9)$$

where P_{Th}/P_{Nd} is normalized for each calculation to optimally fit the data. Actual numerical values range from ~ 1-2. Since the data were normalized to a mean of unity anyway (Butcher 1987) such normalization for production ratios is reasonable.

This ratio is plotted in figure 1 as a function of stellar age for various choices for T_0. These are compared with the line ratios given in Butcher (1987). To the data of Table 3 in that paper we have added a point (presumably HR7869) with an age of 12 Gyr which appears in Fig. 3 of that paper. We have assumed a typical age uncertainty for this point of ± 3 Gyr. In addition, since the age of the sun is not subject to the same uncertainties as the the rest of the stellar ages, the sun was always taken to have been born at T_0 - 4.6 Gyr. The ages of the other stars in the sample were scaled by a factor of $T_0/20$.

The calculation of χ^2 for fits to these data included the uncertainties in the line ratio and stellar age by weighting the square of the resuduals with a variance (Bevington 1969) of $\sigma^2{}_i$ = $\sigma^2{}_{yi}$ + $(dy/dx)\sigma^2{}_{xi}$, where y is the Th/Nd ratio, x is the stellar age, and the derivative is evaluated from the model. There is a rather broad minimum in χ^2 for this model at an age of 5.5 Gyr. The 95% confidence (2σ) upper limit for a χ^2 distribution would be at an age of 15 Gyr, and the plotted 99% (3σ) upper limit is 20 Gyr. The reason our 95% confidence limit is so much larger than that quoted in Butcher (1987) can be traced (Pagel 1987) to the neglect of higher order terms in the expansion of Eq. (9) which was used in the Butcher (1987) analysis. As in Butcher (1987) we note that the data point due to HR3018, the apparent oldest star in the sample, is more than 1σ outside the calculated curves for any age, although the reduced χ^2 for the optimum fit is still very close to unity suggesting that the data are not yet good enough to attach too much significance to this deviation.

Model b) loss term included

Consider next the effect of only including the loss term in Eq. (2) but still keeping the production rates for Th and Nd constant and equal. In this model the analytic solution for Th/Nd becomes;

$$Th/Nd = (P_{Th}/P_{Nd})\exp\{-\lambda(T_0-T)\}[B/(\lambda+B)] \times [1-\exp\{-(\lambda+B)T\}] / [1-\exp\{-BT\}] \quad . \qquad (10)$$

The fractional birthrate, B, in the solar neighborhood at the present time is in the range (Tinsley 1977; Miller and Scalo 1979), $0.2 < B < 2.5$ Gyr^{-1}. Explicitly including the effect of the ejection of nondestroyed Th or Nd in the instantaneous recycling approximation would reduce this rate by a factor of 0.6 to 0.9 (Tinsley 1977). This value for B is to be contrasted with the much smaller ^{232}Th decay rate ($\lambda_{Th} = 0.049$ Gyr^{-1}). Thus, the loss due to star formation should completely dominate the loss from ^{232}Th decay. The increased removal of Th and Nd from the ISM will mean that the Th/Nd ratio will depend more sensitively on the production just before incorporation into a star. Therefore, the Th/Nd ratio will show more dramatic time variation as shown in Figure 2 which plots Eq. (10) for a constant $B = 1$ Gyr^{-1}. In this model, there was no minimum in χ^2 for any galactic age, however all ages less than 0.8

Gyr yield a reduced $\chi^2 \leq 1$. The curve for $T_0 = 9$ Gyr corresponds to a 99% confidence (3σ) upper limit to exceed a reduced χ^2 of 1. We note that this result is largely independent of the value for B as long as $B >> \lambda$.

model c) different production rates and loss terms included

Finally, we consider the different production histories for the s- and r-process material. To estimate these we must explicitly compute the quantities in Eq. (8) from an initial mass function, $\phi(m)$, and birthrate function, f(t). For this purpose we use the Miller and Scalo (1979) three segment power-law initial mass function (in units of pc^{-2});

$$\phi(m) \quad \begin{array}{ll} = 42m^{-1.4} & 0.1 \leq m \leq 1 \\ = 42m^{-2.5} & 1 \leq m \leq 10 \\ = 240m^{-3.3} & 10 \leq m \quad . \end{array} \qquad (11)$$

We find little dependence of the Th/Nd ratio on the star formation rate for reasonable variations (Miller and Scalo 1979; Twarog 1980) from exponentially decreasing to constant functions. Therefore, for illustration, we use a constant star formation rate, $f(t) = 1/T_0$. With this choice, the different nucleosynthetic histories are only reflected in the time delay before low-mass stars eject s-process material into the ISM. For the stellar ages we take (Talbot and Arnett 1971), $\tau(m) = 11.7/m^2 + .001$ Gyr, and for the remnant masses we take (Paczynski and Ziolkowski 1968)

$$m_r = \begin{cases} 0 & m \le 0.7 \\ 0.17m + 0.55 & 0.7 \le m \le 5 \\ 1.4 & m \ge 5 \end{cases} \quad . \tag{12}$$

With these input data, Eq. (8) can be easily solved. We have studied the effects on Eq. (8) of varying the infall rate and following the time dependence of M_G. These features have little effect on the Th/Nd ratio. Therefore, for simplicity, assume an infall rate such that M_G remains constant at a present value of $7.5 \pm 1.5\ M_\odot\ pc^{-2}$ (Tinsley 1977). The relative neodymium production mass fractions, $X^s{}_{Nd}$ and $X^r{}_{Nd}$, are fixed by the solar abundances, i.e. the s-process and r-process contributions are equal for a star born at $T = T_0 - 4.6$.

The results for different T_0 are given in Fig. 3. Models with T_0 from 5 to 8.5 Gyr give equivalently good fits and a reduced $\chi^2 \le 1$. The (2σ) and (3σ) upper limits are at 10 and 13 Gyr respectively. Note that with the different production rates included there now appears to be a natural explanation for the apparently high Th/Nd ratio in HR3018 as well as the nearly constant ratio for stars born later. It would be extremely useful to have more Th/Nd measurements for stars with large ages and low metallicity. It appears from this analysis that HR3018 may have formed within a few billion years of the first heavy-element nucleosynthesis. Also note that the predicted increased Th/Nd ratio early on allows for much larger galactic ages than when the s-process contribution to Nd is neglected (model b).

From these analyses we conclude that simple models of galactic chemical evolution can fit the Th/Nd line ratios with ages as large as 20 Gyr, although our most detailed analysis favors an upper limit of 13 Gyr.

This limit, however, could further increase in models with a bimodel initial mass function (Larson 1986) and/or scaling of the s-process yields with the build up of Fe seed. Therefore we conclude that the Th/Nd line ratios do not necessarily require short galactic ages, but they do give us interesting information on the early history of the galaxy.

V. Acknowledgement

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Figure Captions

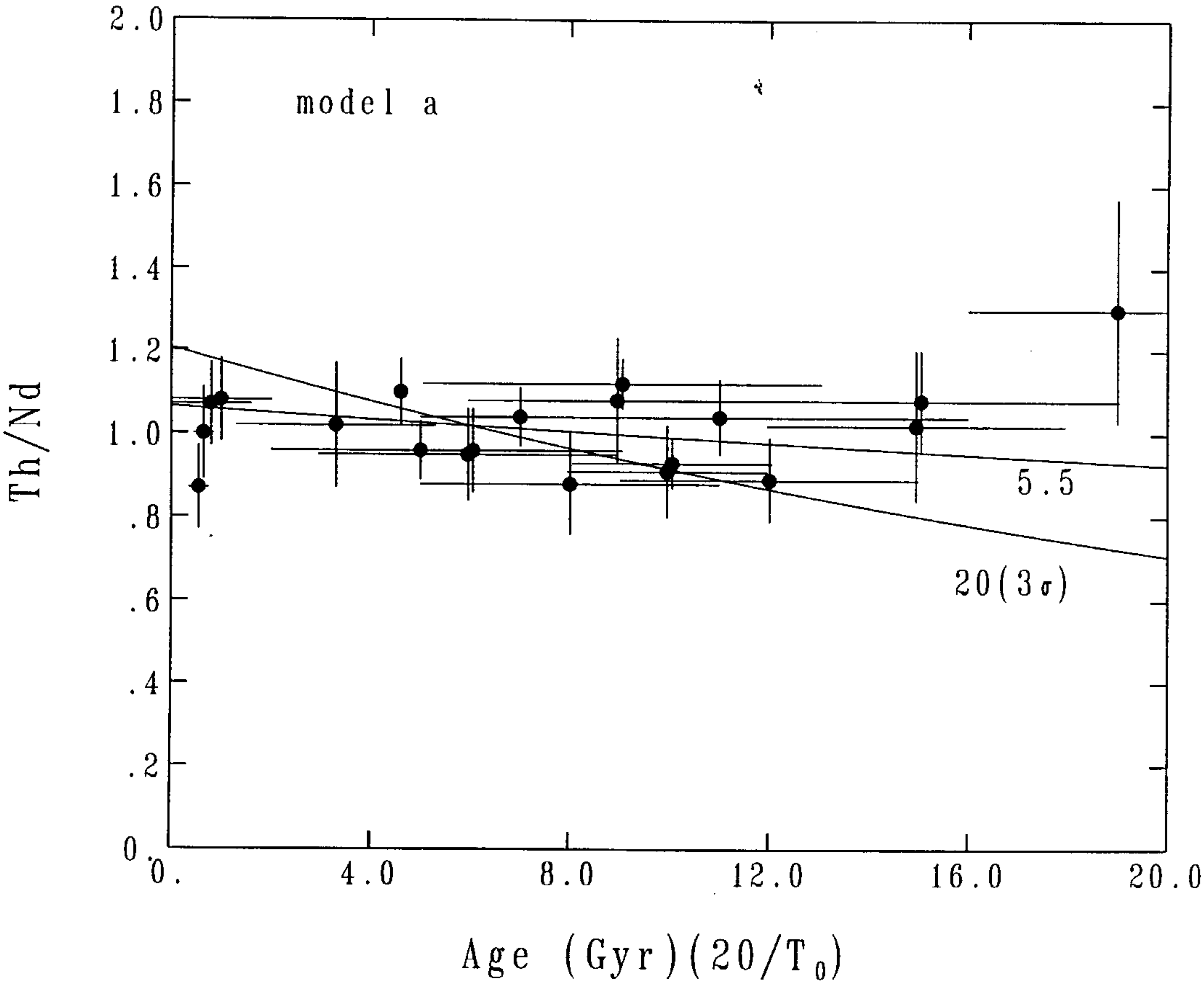
Figure 1) Measured Th/Nd line ratios (Butcher 1987) as a function of apparent stellar age compared with calculated ratios. These calculations are based upon a model similar to that used in Butcher (1987) which ignores the destruction due to star formation and the different nucleosynthetic histories of Nd and Th. The curve for $T_0 = 5.5$ Gyr corresponds to the optimum galactic age in this model. The curve for 20 Gyr corresponds to the 3σ upper limit to this galactic age.

Figure 2) Th/Nd line ratios compared with calculations based upon a model which includes loss of Th and Nd from the ISM as new stars and stellar remnants form. Including this term increases the dependence of the Th/Nd ratio on stellar age. The curve for $T_0 = 0.8$ Gyr corresponds to the maximum galactic age which yields a reduced $\chi^2 \leq 1$. The curve for 9 Gyr corresponds to the 3σ upper limit (99% confidence) to exceed a reduced χ^2 of 1.

Figure 3) Th/Nd line ratios compared with calculated ratios as a function of stellar age. In this calculation a constant rate of star formation was assumed but the s- and r-process contributions were assumed to take place in stars of different mass. The effect of these different histories is to improve the fit to the observed ratios. The curve for $T_0 = 8.5$ Gyr corresponds to the maximum galactic age which yields a reduced $\chi^2 \leq 1$. The curve for 13 Gyr corresponds to the 3σ upper limit (99% confidence) to exceed a reduced χ^2 of 1.

Note Added Proof:

Similar studies and conclusions have been obtained in separate papers recently submitted to Nature by D. N. Clayton and W. A. Fowler.



model a
5.5
20(3σ)
Th/Nd
Age (Gyr)(20/T0)
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0.
4.0
8.0
12.0
16.0
20.0

Fig. 1

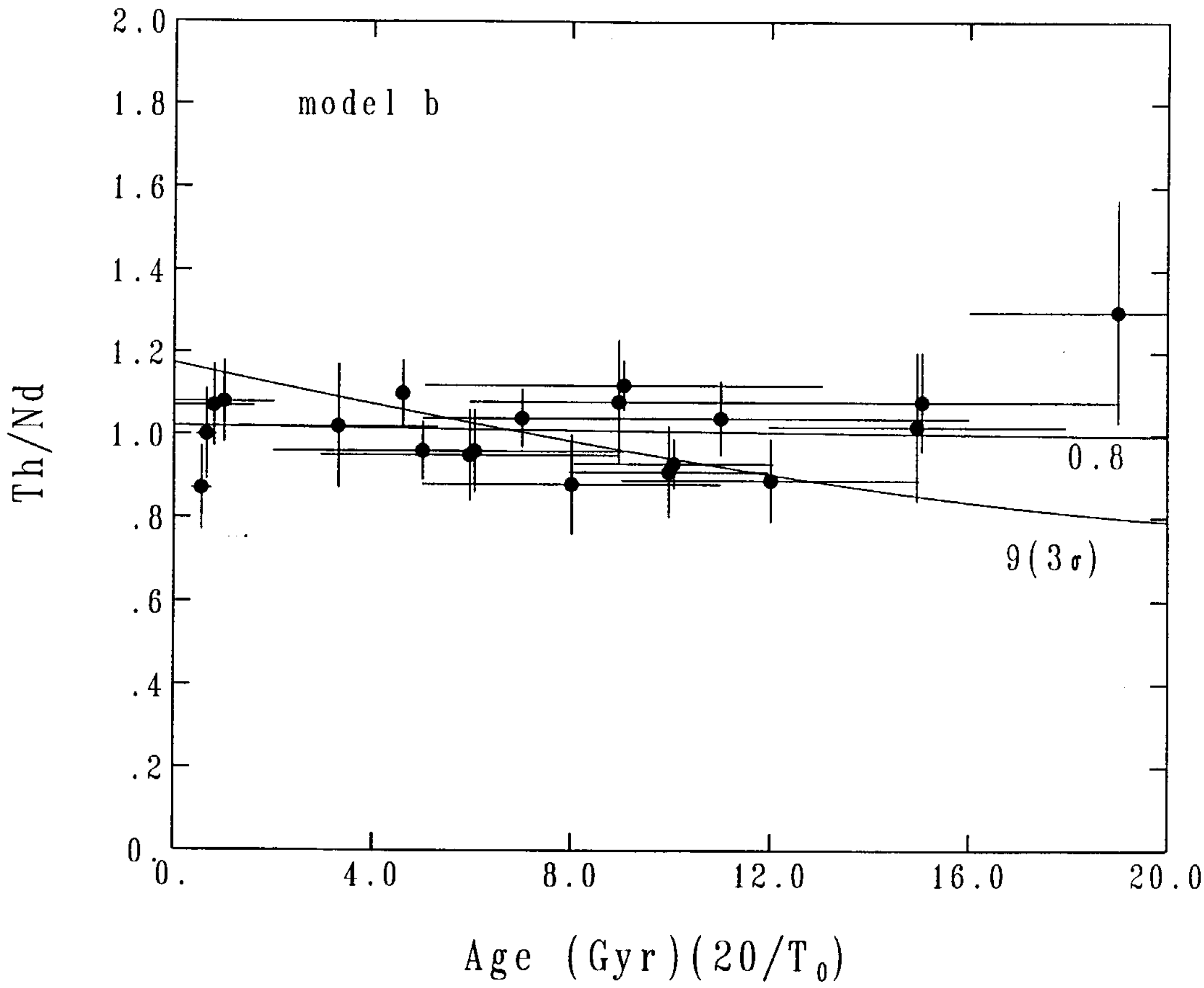

model b
0.8
9(3σ)
Th/Nd
Age (Gyr)(20/T0)
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0.
0.
4.0
8.0
12.0
16.0
20.0

Fig. 2

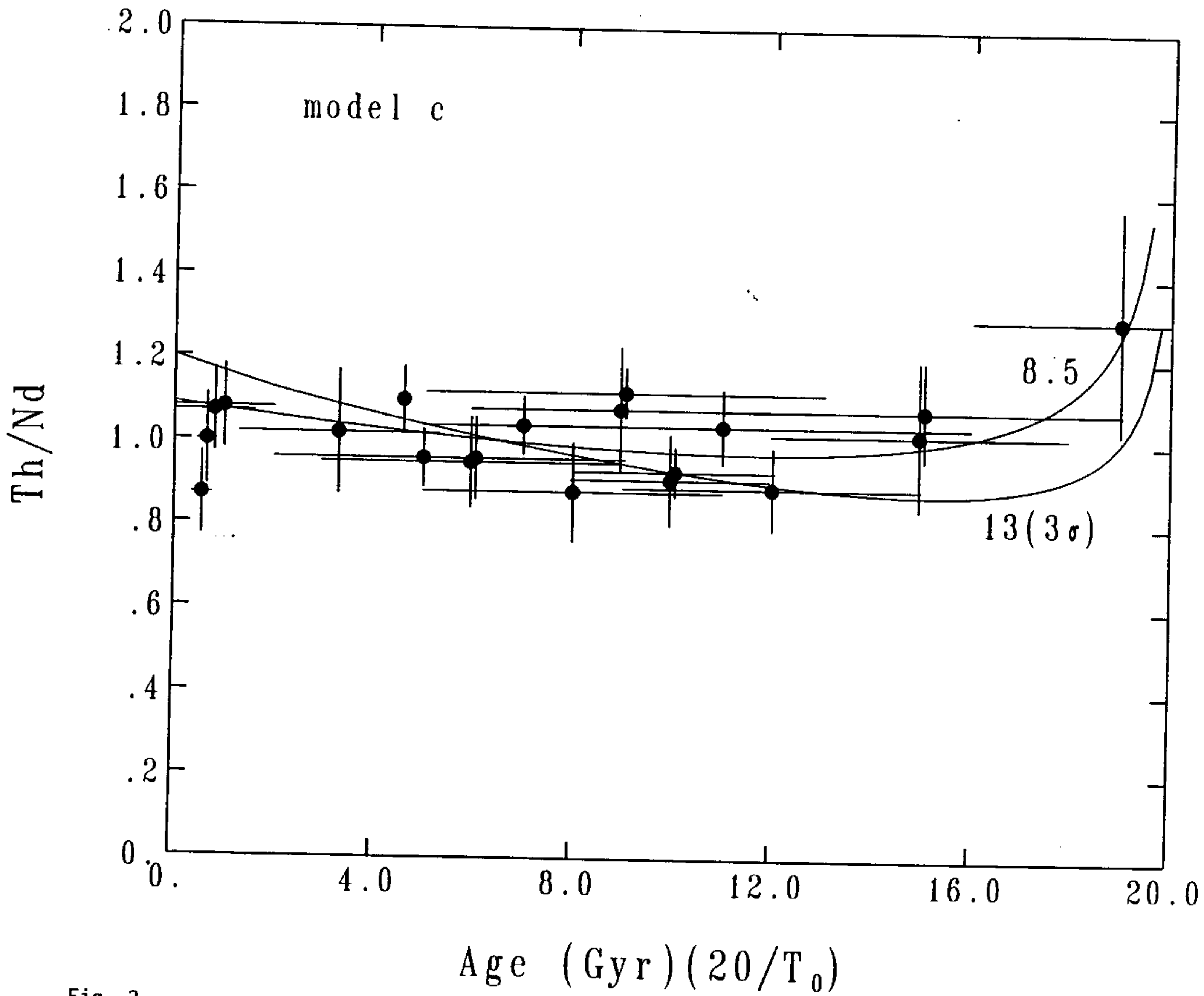

model c
8.5
13(3σ)
Th/Nd
Age (Gyr)(20/T0)
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0.
0.
4.0
8.0
12.0
16.0
20.0

Fig. 3